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Thermo-fluid dynamic analysis of concrete masonry units via experimental testing and numerical modeling

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ABSTRACT

This study aims to achieve a better understanding of the thermal behavior of concrete masonry systems, focusing not only on standard units but also on special thermally efficient unit configurations. In this context, sophisticated numerical models are generated to predict the thermal performance of masonry units. The validation of these numerical models follows a rigorous process that includes comparisons against experiments in the laboratory. The validated models are then used to evaluate the effect of material properties, geometry, and insulated materials on the heat flow path, distribution of temperatures, and air velocities within the units. The results show the importance of including the three heat transfer mechanisms of conduction, convection, and radiation within an effective numerical model and the equal importance of considering the influence of air flow within the cells of the masonry units.

1. Introduction

The concrete masonry unit (CMU) is a widely-used construction material whose annual production is estimated at 4.3 billion units in the United States and Canada [1–3]. The thermal efficiency of CMUs is quantified in terms of the units' thermal resistance (R-value) [4–6], where a higher R-value represents increased thermal efficiency caused by effective insulation properties [7]. In the past, studies conducted on CMUs have used simplified methods of calculating R-values (e.g., series, parallel path, isothermal planes, zone methods) [8–12]; however, these simplified methods have proven insufficient for representing the effect of complex three-dimensional air flow within the unit's molded interior space (also known as a cell) on the thermal performance of the CMU [13–18]. Different unit configurations (e.g., cell geometry, masonry material properties, the use of insulated materials) affect the air flow within the cells and thus influence the R-value of the unit. Taking the air flow into account in thermal analysis has the potential to improve the current state of knowledge regarding the thermal behavior of CMUs, and this increase in knowledge could, in turn, allow for unit design improvements [19,20].

In the thermal analysis of CMUs, it is critical to consider not only air flow within the cells but also the three key mechanisms of heat transfer (i.e., conduction, convection, and radiation). For instance, changes in unit geometry may alter the paths of heat conduction through the unit (i.e., thermal bridges). In cases where the geometries of CMU cells are altered, the air flow within cells can increase or decrease the heat transported by convection through the air between the inner faces of the unit. Modifying the CMU by adding insulating materials or barriers within the cells affects heat radiation, as energy is emitted by electromagnetic waves or photons emanating from the inner faces of the cells [21,22]. Despite the importance of radiation in determining the thermal performance of CMUs, the established literature on the subject has primarily focused on the heat transfer mechanisms of conduction and convection [19,23–25]. Only recently have studies conducted on the thermal behavior of CMUs begun to consider radiation in addition to conduction and convection [18,26–28]. Because such studies are few and far between, the effects of different design parameters on the three mechanisms of heat transfer have not yet been fully understood. Such an understanding is essential for the design of new CMU configurations with improved thermal behavior.

In this paper, the authors perform a combined experimental and numerical study to investigate the effects of a variety of CMU design decisions (e.g., altering the unit geometry and thus the thermal bridges of heat conduction) on the thermal efficiency of CMUs. Addressing the gaps in the pertinent literature, the present study considers the influence of air-filled cells on the thermal behavior of CMUs and takes all

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three heat transfer mechanisms of conduction, convection, and radiation into account. The study involves an experimental testing campaign in a hot-box, as well as the construction of detailed three-dimensional computational fluid dynamic models that are used to conduct thermo-fluid dynamics simulations. The authors recognize that both experimental tests and numerical simulations are important for gaining an improved understanding of the thermal behavior of CMUs. Simulations without experiments are speculative, and experiments without simulations are constrained within the scenarios tested [29–32]. In this study, experiments are conducted with the purpose of validating the simulations through rigorous test-analysis comparisons. The validated numerical models are then used to predict the thermal performance of untested CMUs and to explore different design configurations see additional examples of using validated models in the evaluation of other construction materials in Ref. [27,33–36].

This paper is organized as follows: Section 2 details the experimental and numerical research campaign. The description and development of the three-dimensional numerical models and thermo-fluid dynamics simulations are discussed in Section 3, as are the material properties (i.e., air density, air heat capacity, and thermal conductivity) of the CMUs and the details related to the model convergence study that is used to determine the optimal mesh size. Section 4 describes the hot-box test of the CMUs in laboratory, and Section 5 covers the experimental validation of the CMU numerical models. In Section 6, the previously validated numerical models are used to predict the response of the CMUs for the different unit and insulation types investigated in the research campaign. Finally, Section 7 offers a discussion of the feasibility of using the new CMU configurations in the construction industry, while Section 8 contains concluding remarks and directions for future research.

2. Research campaign

This study implemented a hierarchical research campaign that started from small-scale coupon testing and ended with a system-level evaluation of a CMU, as shown in Fig. 1. Material properties such as thermal conductivity and heat capacity were obtained through the laboratory tests on the small-scale coupons (Fig. 1a) and were then used as input parameters while developing the numerical models of the units (Fig. 1b). Next, tests were conducted on the units to assess the validity of the numerical models for predicting the thermo-fluid dynamic behavior of the CMUs (Fig. 1c). The experimentally validated numerical models were then executed to evaluate various CMU configurations (Fig. 1d) that altered (i) units' web configuration (and thus thermal bridging) for heat conduction and (ii) air movement within the units' cells for convective and radiative heat transfer.

With the objective of gaining a better understanding of the effect of a variety of CMU design decisions on the thermal efficiency of CMUs, the authors evaluated 24 different CMU configurations with different unit and insulation types. "Unit type" will hereafter refer to the unit geometry of particular CMUs, while "insulation type" will refer to the type of insulation (or lack thereof) used in particular CMUs. When speaking of a particular unit type that has a particular insulation type, we will use the phrase "configuration type."

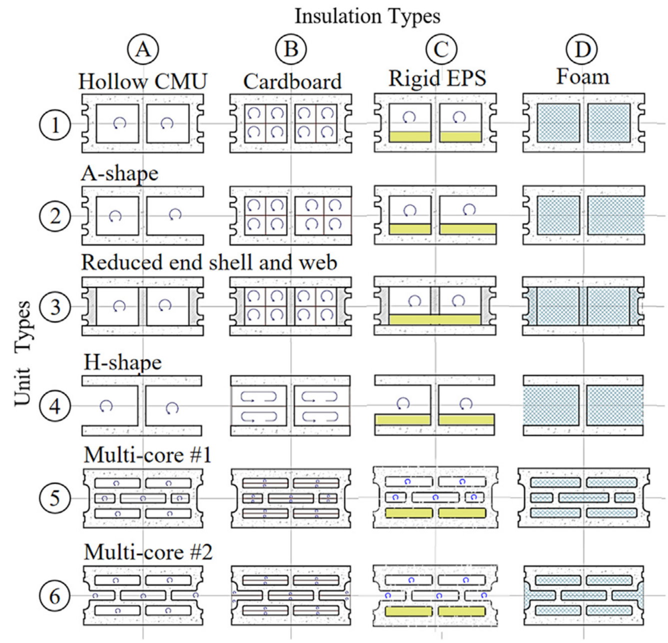

Fig. 2. CMU insulation types and unit types investigated in this study. The horizontal rows represent different unit types (e.g., 1–6), while the vertical columns represent different insulation types (i.e., different insulation material) (e.g., A-D). Configuration types are composed of a particular unit type and a particular insulation type (e.g., A1-D6).

Below, Fig. 2 illustrates the different unit and insulation types used in this study. The four columns in the figure represent *different insulation types* in the CMU cells: Column A is the conventional hollow 8 × 8 × 16 CMU; Column B includes extruded cardboard; Column C includes rigid expanded polystyrene (EPS); and Column D includes injected foam insulation (polyurethane foam). The six rows in Fig. 2 represent the *different unit types*: Row 1 is a hollow unit; Row 2 is an A-shaped unit; Row 3 is a unit with end shells and web of reduced height; Row 4 is an H-shaped unit; Row 5 is a multi-core unit with continous end shells; and Row 6 is a multi-core unit with discontinous end shells. For four of the 24 configuration types (Row 1, from A1 to D1), the numerical models were validated against laboratory experiments, and the remaining 20 configuration types were predicted using the validated numerical models.

The research campaign shown in Fig. 2 allowed for a comparison between the thermal performance of the conventional hollow CMU and the thermal performance of units with different unit types (e.g., alternative webs and end shells) and different insulation types (i.e., different types of insulation material). In this comparison, thermal efficiency was

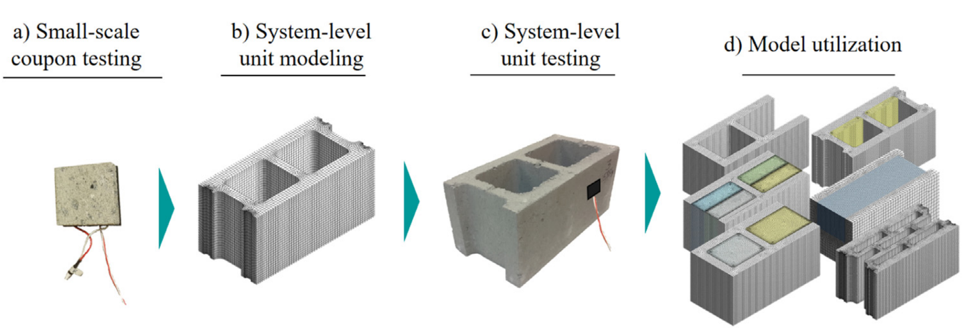

Fig. 1. Hierarchical process to study thermal performance of CMUs: a) small-scale coupons, b) numerical models of the units, c) experimental test of the units, and d) model utilization.